



# Mitigating Air Risk of Drone Operations in Low-level Airspace with a 4D Trajectory U-space Framework

Thomas Dubot, Antoine Joulia

## ► To cite this version:

Thomas Dubot, Antoine Joulia. Mitigating Air Risk of Drone Operations in Low-level Airspace with a 4D Trajectory U-space Framework. AIAA AVIATION 2023 Forum, AIAA, Jun 2023, San Diego, United States. <10.2514/6.2023-4109>. <hal-04625700>

**HAL Id: hal-04625700**

**<https://hal.science/hal-04625700v1>**

Submitted on 26 Jun 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

# Mitigating air risk of drone operations in low-level airspace with a 4D trajectory U-space framework

Thomas Dubot\* and Antoine Joulia†

*ONERA/DTIS, Université de Toulouse, Toulouse, France, F-31055*

U-space, the drone traffic management framework in Europe, is deploying advanced services to ensure safe and efficient air traffic management in low-level airspace. In urban areas, drone operations must mitigate the risk of mid-air collisions, or air risk, with both manned and unmanned traffic, whether planned or not. To address these challenges, we have developed an innovative solution that utilizes virtual 4D protection bubbles around drones. We present here an extension of this 4D trajectory-based model to incorporate the air risk associated with unplanned traffic. Protective bubbles are formed, ensuring sufficient separation from planned traffic, while also serving as a risk indicator throughout the trajectory. To demonstrate the efficacy of this approach, we present an operational use case based on the delivery of blood bags over a densely populated area. We also detail the construction of a basic risk model that combines a set of risk layers using data from geographically risky areas and historical traffic data. Finally, we explain how a suite of U-space services can leverage this 4D framework to evaluate and mitigate the air risk incurred by drones flying in low-level airspace.

## I. Introduction

THE safe operation of Unmanned Aircraft Systems (UAS), also known as drones, at low-level airspace has driven significant advancements in technology, operations, and regulations over the past decade. NASA's UAS Traffic Management (UTM) initiative [1] paved the way for the development of drone traffic management frameworks, similar to the Air Traffic Management (ATM) system for conventional aviation. In the US, the Federal Aviation Administration (FAA) has released its UTM concept of operations [2], while in Europe, the SESAR Joint Undertaking (SJU) has produced the U-space Blueprint [3], defining the principles of U-space (the European UTM counterpart) and outlining four levels of implementation of U-space services, or U-levels (U1 to U4). The CORUS project (Concept of Operations for EuROpean UTM Systems) released the first U-space concept of operations in 2019 [4], which was updated in 2022 [5] to integrate Urban Air Mobility (UAM) operations. To standardize UTM initiatives globally, the International Civil Aviation Organization (ICAO) released its third edition of UTM - A Common Framework with Core Principles for Global Harmonization in 2023 [6].

In parallel, the European Commission released in 2019 an implementing regulation on the rules and procedures for the operation of unmanned aircraft [7], and in 2021, a regulatory framework for the U-space [8]. These documents both emphasize the need for 4D trajectory during the operation plan preparation stage, as well as the necessity to define and formalize geographical zones in order to address risks pertaining to safety, privacy, protection of personal data, security, or the environment inherent in low-altitude drone operations.

[5] provides a mapping table with the different names and associated U-levels for the large number of U-space services introduced in both CONOPS and regulation documents. In our previous work [9, 10], we examined the implementation of 4D protection bubbles as a means of supporting conflict management services (prediction and resolution), ranging from strategic to tactical phases. We focus in this paper on the ability of a set of U-space services to integrate such a 4D framework, by extending the concept so that 4D protection bubbles are also constructed based on the potential air risk induced by unplanned traffic.

In Section II, we provide a brief summary of the U-space services. In Section III, we detail how U-space services can be facilitated by 4D trajectories and protection bubbles. In Section IV, we describe our operational use case, based on a blood bag delivery service between two hospitals in the city of Toulouse, France. In Section V, we present a model for evaluating and mitigating air risk based on a combination of risk layers, and then we analyze how a U-space framework can be used to detect these risks and propose initial mitigation. Finally, Section VI summarizes the conclusions, the limits and the perspectives of this study.

---

\*Research engineer, Information processing and systems Department, thomas.dubot@onera.fr.

†Research engineer, Information processing and systems Department, antoine.joulia@onera.fr.

## II. U-space services

According to the International Civil Aviation Organization (ICAO) [6], the Unmanned Aircraft Systems (UAS) Traffic Management (UTM) system can be considered as a collection of services, among other features, intended to ensure the safe and efficient operations of drones within authorized airspace volumes. The European version of the UTM system, named U-space, is also defined in a similar way by the Single European Sky ATM Research Joint Undertaking (SESAR JU), which describes it as *"a set of new services relying on a high level of digitalization and automation of functions and specific procedures designed to support safe, efficient, and secure access to airspace for large numbers of drones."* [11]

The SJU's U-space Blueprint [3] defines four U-space levels, ranging from foundation services (U1) such as identification and registration, to full services (U4) offering the highest levels of automation and integration, as detailed in Figure 1 (adapted from [12]).

U1	Foundation	<ul style="list-style-type: none"> <li>▶ Registration</li> <li>▶ Registration assistance</li> <li>▶ e-identification</li> <li>▶ Geo-awareness</li> <li>▶ Drone aeronautical information management</li> </ul>
U2	Initial	<ul style="list-style-type: none"> <li>▶ Tracking [Position report submission]</li> <li>▶ Surveillance data exchange</li> <li>▶ Geo-fence provision [includes dynamic geo-fencing]</li> <li>▶ Operation plan preparation /optimisation</li> <li>▶ Operation plan processing</li> <li>▶ Risk analysis assistance</li> <li>▶ Strategic Conflict Resolution</li> <li>▶ Emergency Management</li> <li>▶ Incident/ Accident reporting</li> <li>▶ Citizen reporting service</li> <li>▶ Monitoring</li> <li>▶ Traffic information</li> <li>▶ Navigation infrastructure monitoring</li> <li>▶ Communication infrastructure monitoring</li> <li>▶ Legal recording</li> <li>▶ Digital logbook</li> <li>▶ Weather information</li> <li>▶ Procedural interface with ATC</li> </ul>
U3	Enhance	<ul style="list-style-type: none"> <li>▶ Dynamic Capacity Management</li> <li>▶ Tactical Conflict Resolution</li> <li>▶ Geospatial information service</li> <li>▶ Population density map</li> <li>▶ Electromagnetic interference information</li> <li>▶ Navigation coverage information</li> <li>▶ Communication coverage information</li> <li>▶ Collaborative interface with ATC</li> </ul>
U4	Full	<ul style="list-style-type: none"> <li>▶ Integrated interfaces with manned aviation</li> <li>▶ Additional new services</li> </ul>

**Fig. 1 SESAR U-space service levels.**

The European U-space regulation [8] has identified four initial mandatory services to be deployed at the U1 level, namely network identification, UAS flight authorization, geo-awareness, and traffic information.

In a similar way, the CORUS consortium's latest edition [5] (CORUS-XUAM) summarizes these U-space services for levels U1 to U3, including the four aforementioned mandatory services.

Given our focus on assessing and mitigating the risk of mid-air collisions in shared low-level airspace, we are considering a vast array of U2 level services, including strategic conflict resolution and tracking services. We are also looking into an initial implementation of tactical conflict prediction and resolution services that are currently planned for the U3 level.

## III. A 4D trajectory framework for conflict management services

Conflict management refers to the process of preventing aircraft to operate too close to each other, i.e. with a separation distance below an agreed separation standard. This process is usually divided into two tasks:

- conflict detection: the identification of two aircraft operating (or about to operate) too closely;
- conflict resolution: the actions to be performed in order to go back to an adequate separation.

The most important aspect of conflict management should take place during the strategic phase, through a coordinated process based on flight demands. However, this is not always sufficient, as unexpected events such as weather phenomena may require tactical updates. We have proposed in [9, 10] the use of 4D trajectories and 4D protection bubbles to facilitate conflict management services. The following paragraphs provide a summary of the usage of this 4D trajectory framework in both the strategic and tactical phases.

During the strategic phase, UAS operators provide their flight plans to U-Space Service Providers (USSPs). The UAS operator submits a flight authorization request to the USSP responsible for the U-space airspace. According to Annex IV of the European Commission’s regulatory framework for U-space [8], this UAS flight authorization request must include a 4D trajectory. The USSP then augments these trajectory data with additional information gathered from various sources, such as other U-space services, UAS operators, or external sources. This includes considering factors like weather predictions or airspace constraints.

This 4D protection bubble allocation process is used to create a conflict-free traffic through the following steps:

- Upon completion of the optimization process, all 4D trajectories, as agreed upon by drone operators, are deconflicted. As a result, as long as all aircraft stay within the boundaries of their respective 4D bubbles, there will be no aircraft operating in dangerously close proximity to one another.

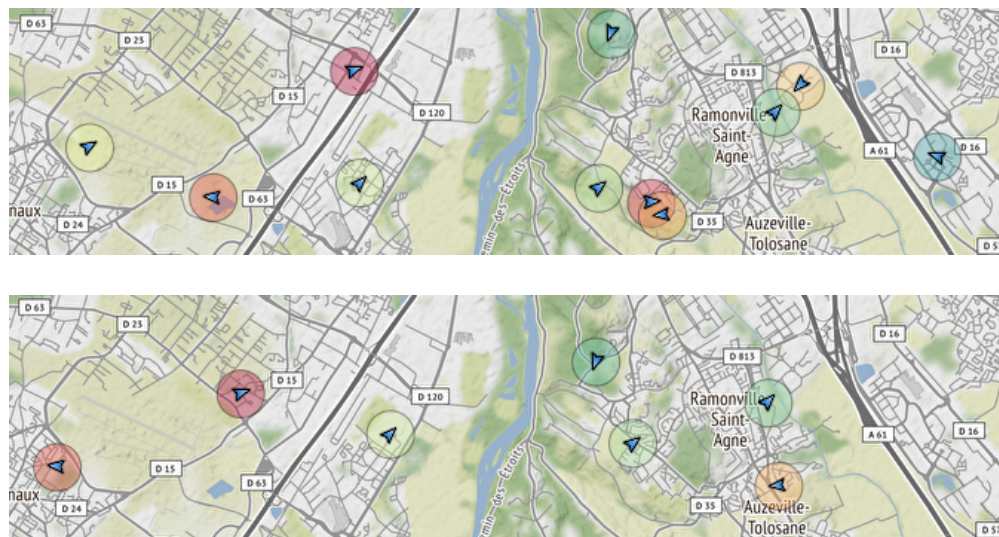


Fig. 2 illustrates the result of this optimization phase with a zoom on a district of a large French city. The top image displays the situation before the optimization, where the original flight demands would lead to the intersection of two pairs of protection bubbles, which is an undesirable outcome. In contrast, the bottom image demonstrates the outcome of an optimization process employing take-off time-shift, which successfully mitigated the previously detected bubble overlaps to ensure a safe and conflict-free traffic [9].

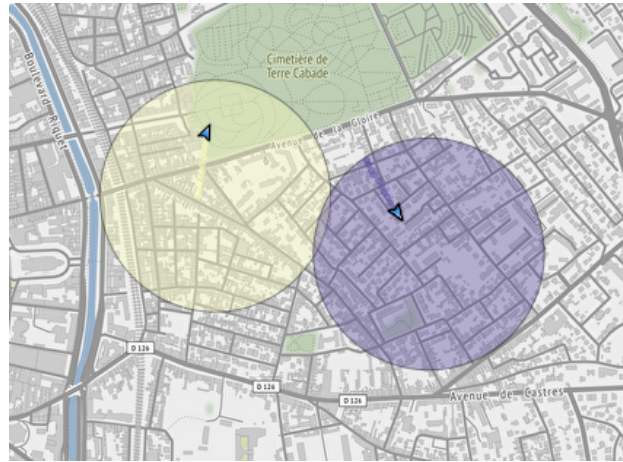
## B. Tactical layer

As previously indicated, the tactical phase of the flight remains critical in terms of conflict management, as various types of uncertainties (mission updates, weather variations, airspace access restrictions) may arise after take-off. These uncertainties are likely to cause deviations between the planned (conflict-free) trajectories and the ones that are actually flown by the drones. Therefore, it is crucial to manage this air risk by detecting and resolving potential conflicts. To ensure the highest level of safety, responsibility for managing the air risk is shared among all actors involved in the drone flight. 4D protection bubbles, combined with other U-space services, are a crucial enabler for conflict detection at both the onboard and supervision levels.

### 1. Conflict detection

4D protection bubbles are employed to identify potential conflicts surrounding aircraft:

- At the vehicle level, it is the drone's responsibility to remain within the boundaries of its assigned 4D protection bubble during flight. Techniques like geocaging strategies [15] can be employed to achieve this goal. The UAS operator is responsible for ensuring that the drone stays within its bubble, with the assistance of U-space services such as monitoring service. If there is a risk of bubble excursion, the UAS operator must promptly notify the USSP of this potential risk.
- At the supervision level, the USSP monitors the traffic under its jurisdiction to identify trajectories that deviate from the planned ones. This task is facilitated by a subset of U-space services and information that is directly provided by UAS operators.



**Fig. 3 Intersection of bubbles requiring limited action**

When a deviation between planned and actual trajectories is detected, the USSP is in charge of evaluating the potential conflict risk. If the risk is limited, as illustrated in Fig. 3, the USSP can perform a minor trajectory update for the deviating drone to ensure that it remains conflict-free for the remainder of the flight. However, if there is a significant risk of conflict, the USSP shifts to conflict resolution mode.

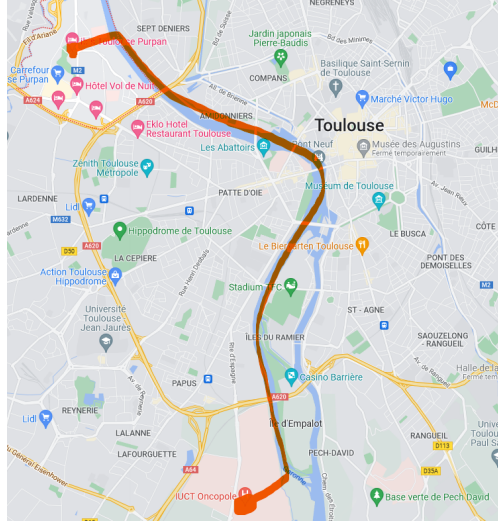
### 2. Conflict resolution

Once a risk of conflict between two aircraft is detected, the conflict resolution phase is initiated. In this phase, new 4D trajectories with associated 4D protection bubbles must be generated and communicated to all drones involved in the conflict, either directly or indirectly. A local cluster-based computation of conflict-free trajectories is performed to ensure the safety of the drones, taking into consideration various factors such as drone positions, aircraft performance limitations, and weather updates. As detailed in [16], this computation prioritizes actions on the faulty drone and attempts to minimize the impact on the rest of the traffic, as well as any potential domino effect. Once the updated trajectories are generated, they are communicated to the drone operators, and a new monitoring phase begins to ensure the safety of the drones.



#### IV. Operational use case

The aim of the following use case is to implement a drone system that can transport blood bags between two hospitals situated in the city of Toulouse, France. Since the two hospitals are in the immediate periphery of the city center, direct trajectories would require flying over a dense urban area, as depicted in Fig. 4.



**Fig. 4 Delivery of blood bags in dense urban area**

The proposed system involves a fleet of several drones that can operate concurrently with low traffic density. To minimize the need for segregating airspace for specific drones, we require the deployment of a drone traffic management system. We aim to describe this system's U-space implementation by detailing the required U-space services and associated airspace. At minimum, we assume the availability of a surveillance service that can monitor all traffic at low altitudes.

This operational use case is feasible in the short-term, however, it requires the deployment of several U-space services of U-space level 2. In addition, there may be an early implementation of some services of U-space level 3, such as tactical conflict resolution, to ensure the safe and efficient operation of the system.

We assume that the 4D framework described in Section III will be used by many U-space services of the traffic management system. Each drone flight is hence defined by a 4D trajectory with associated 4D protection bubbles. In our low-altitude scenario primarily involving drones and helicopters, we have determined that implementing a single layer is more appropriate. This is due to the need for drones to avoid flying below helicopters. As such, a singular altitude layer is utilized, and protective bubbles can be envisioned as cylinders originating from the ground and extending to the upper boundary of the low-altitude layer, augmented with a slight security margin. Even though we only work with 3 dimensions (latitude, longitude, and time), we will continue to use the terms 4D trajectory and 4D protection bubbles to avoid any confusion about the absence of time information. In the next section, we will detail how the variation of the protection bubbles' radius could help to mitigate the risk of collision.

As part of the risk assessment for encounters with other low-level traffic, one of the primary concerns is the possibility of encountering emergency helicopters. This is particularly relevant for our use case, as the main heliport for the city is located in one of the two hospitals and may be used for operations similar to those of our drone fleet. In the event of such an encounter, we will apply the right-of-way rule established in the CORUS CONOPS [5], which requires drone flights to give way to crewed flights.

Two scenarios have been considered for this use case:

- 1) Operation in nominal conditions: This scenario illustrates the expected proceedings of the use case. It involves the cohabitation of new drone operations with other traffic, strategic planning of safe operations with 4D trajectories, dynamic management of encounter risk, and a return to normal operations process.
- 2) Operation in abnormal conditions: In this scenario, one of the aircraft operating within the U-space area of responsibility exhibits abnormal behavior due to safety reasons (e.g., a malfunction of an aircraft component) or security reasons (e.g., aircraft spoofing).

## V. Assessing and mitigating air risk

### A. Building a risk proximity layer from UAS geographical zones

The size of the protection bubble should be adaptable, depending on the local traffic density. In areas where drone positioning accuracy is crucial due to high traffic density, the bubble size is minimized to reduce the risk of collision. On the other hand, in low-density areas where the risk of encounter is low, enlarging the bubble provides more flexibility to the drone operator in managing the flight.

However, this process only applies to aircraft that file a 4D trajectory before the flight, such as other drones from the same fleet or another fleet of drones. Meanwhile, other traffic, including emergency helicopters, shares the same low altitude airspace. Such airspace users are not integrated into the 4D bubbles optimization process, and thus, this "unplanned traffic" has to be treated specifically. However, it is necessary to take them into consideration when defining the 4D protection bubbles to fully benefit from the underlying services. To model the air risk associated with the unplanned traffic, we suggest using the same 4D protection bubbles. We computed the radius of the protection bubbles based on the probability of encountering unplanned aircraft: the higher the probability, the smaller the bubble radius.

When planning a mission, it is important to consider the geographical area in which it will take place. In accordance with regulatory documents [7, 8], a geo-awareness function must be implemented to comply with the following requirements: Firstly, UAS geographical zones must be defined as portions of airspace that facilitate, restrict, or exclude UAS operations to address risks related to safety, privacy, protection of personal data, security, or the environment. Secondly, drone operators must be provided with up-to-date information on airspace constraints. Finally, potential breaches of airspace limitations must be detected, and pilots must be alerted to take immediate action.

In compliance with Article 15 of [7], which deals with the provision of UAS geographical zones, the Aeronautical Information Service (SIA) in France provides this information, along with a user guide [17] that elucidates the nature and reasoning behind the designated zones. The zone descriptions are characterized by the "reason" field, which may be labeled "air traffic" in cases where restrictions are associated with the risk of mid-air collisions with typical zone traffic. However, other areas (tagged as "other", for example) also deserve to be considered in our context. We assign manually a weighting factor to each type of identified zone. Subsequently, we create a risk matrix by converting the map of the area into a matrix where each cell is assigned a value, from 0 (no risk) to 1 (very high risk), based on the risk factor of the surrounding zones, taking into account a decreasing function of the distance to the barycenter of each zone.

$$s_r(x, y) = \sum_{i=1}^n w_i \cdot \frac{1}{d_i(x, y)^\beta} \quad (1)$$

where  $n$  is the number of zones,  $w_i$  is the weight of zone  $i$ , and  $d_i(x, y)$  is the distance from zone  $i$  to the barycenter.

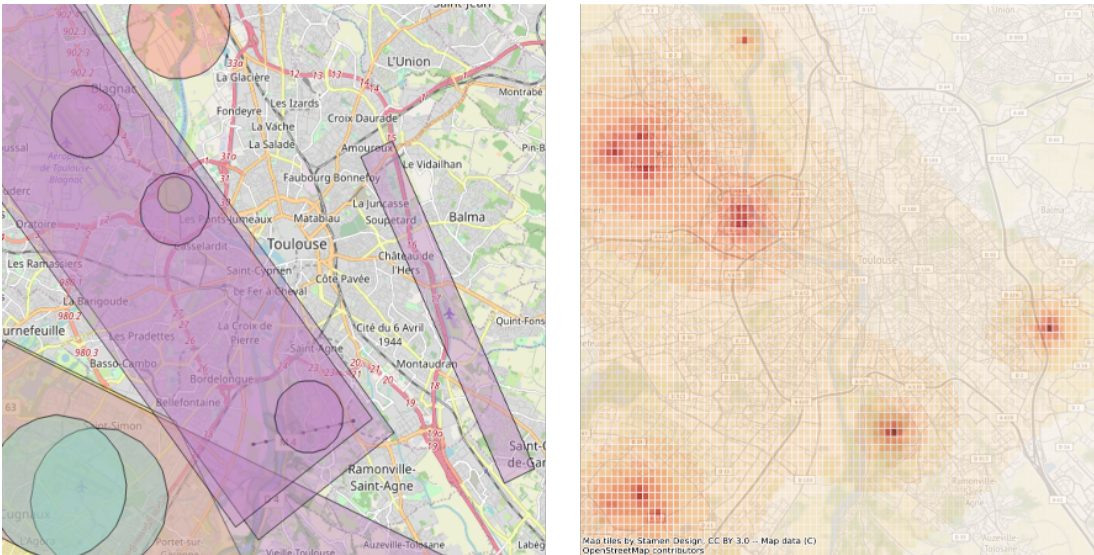


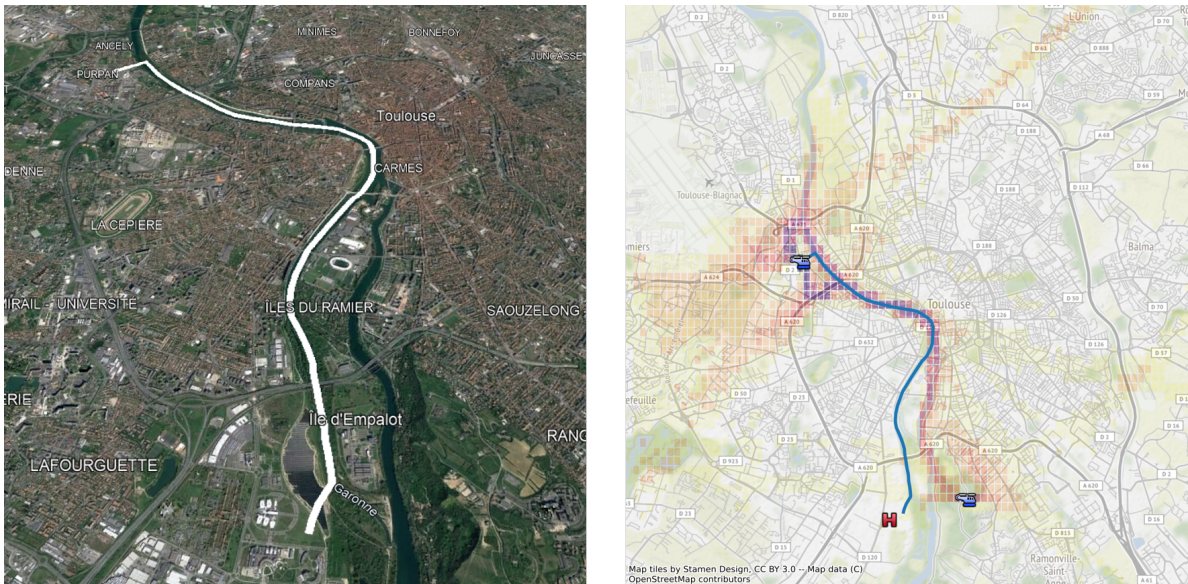
Fig. 5 Using UAS geographical zones (left) to build proximity risk layer (right)

The outcome of our analysis is a proximity risk layer that is represented by pixels, as depicted in Fig. 5. The red dots visible in the image, for instance the one located above Toulouse-Blagnac International Airport (northwest of the picture), indicate a high likelihood of encountering air traffic based on the declared UAS geographical zones.

## B. Building traffic density layers from ADS-B data

An alternative approach to modeling the air risk linked to a specific geographical zone involves utilizing historical flight data. For this purpose, we employed Automatic Dependent Surveillance-Broadcast (ADS-B) data that was collected and provided by the OpenSky Network [18]. Specifically, we analyzed all recorded trajectories by ADS-B receivers in low-level airspace above the Toulouse area during the year 2022. To facilitate analysis, we categorized the trajectories based on traffic type, such as commercial, general, or military aviation, as well as helicopters.

Next, we combined this data to construct two-dimensional (2D) heatmaps for the specific zone considered in our use case. Each heatmap depicts the density of a particular traffic type across the cells of the geographic matrix. Similar to the proximity layer described in the preceding paragraph, these density layers can be utilized by drone operators in the strategic phase, especially when designing the initial trajectory routes. Drone operators can use these density layers to replicate some of the relevant trajectory patterns while avoiding zones that are likely to be congested.



**Fig. 6 Drone operator path and corridor (left) versus emergency helicopter traffic density layer (right)**

On Fig. 6, the left image depicts the drone initial path (north to south), designed by the drone operator to comply with requirements of the operational use case. On the right, this drone initial path is superimposed on the density layer of emergency helicopter traffic. It can be observed that both drone and helicopters aim at performing the most part of the flight above the river. However, whereas helicopters seem to follow a departing procedure, the drone aims at reaching the river with a direct path. The first leg of the drone flight follows a high density corridor, but as soon as an alternative becomes available (a secondary arm of the river, which is almost not used by helicopter traffic), the drone operator opts for a lesser-risk path.

## C. Building trajectory protection bubbles from layers

Once the drone operator's initial trajectory is received, a 4D trajectory can be generated, incorporating protection bubbles whose size varies along the route. While the bubble size can be adapted to ensure separation from other aircraft's 4D trajectories, it can also serve to model and visualize the air risk based on the previously defined layers, namely the risk proximity layer and traffic density layers. When the combination of these layers indicates a high risk of encounter, the radius of the protection bubbles is reduced to mitigate the risk. This approach enhances situational awareness by providing the drone operator with a real-time visual representation of the airspace risk level along the intended path.



After normalizing the risk scores of all relevant layers and assigning weighting factors to each layer based on their relative importance, we utilized a weighted sum to calculate the radius of the protection bubble at regular intervals. Note that these weighting factors are unrelated to those used to construct the proximity risk layer.

$$r(x, y) = r_{max} - (r_{max} - r_{min}) \sum_{i=1}^n w_i s_{r_i}(x, y) \quad (2)$$

where  $n$  is the number of layers,  $w_i$  is the weight of layer  $i$ , and  $s_{r_i}(x, y)$  is the risk score of layer  $i$ .



**Fig. 7 Variation in bubble size depending on weights of risk layers: priority to UAS geographical zones (left), priority to helicopter traffic (right)**

Fig. 7 demonstrates the impact of weighting factors assigned to each layer on the final result. The left image shows the bubbles when the risk proximity layer is given the highest priority. The right image shows the bubbles when the emergency helicopter traffic density layer is given the highest priority. The obtained results differ significantly.

Protection bubbles can clearly become a key enabler for air risk mitigation, both at strategic and tactical levels. During the strategic phase, the size of the bubbles provides the drone operator with a clear visual indication of the portion of the flight plan that deserve the most attention. This may prompt the drone operator to modify the initial route or focus on risk mitigation strategies in specific areas, such as identifying emergency landing zones. In the tactical phase, the bubbles serve as a clear indicator of areas with a high risk of unplanned traffic encounters. Additionally, they provide an efficient means to define a new safe trajectory in case an update becomes necessary.

#### D. Integrating air risk in U-space framework

From a U-space perspective, the current CORUS CONOPS [5] identifies several services that are necessary for the management of drone traffic. As previously analyzed in our earlier articles [9, 10], 4D trajectories are at the core of some of these services. They serve as a means of communication between UAS operators and drone traffic managers for effective sharing of airspace. In fact, we believe that the 4D trajectory concept, including all the enhancements presented in this paper, has the potential to become an implementation for several U-space services as presented in the table below.

Service	Description
<b>Conflict prediction and resolution</b>	4D protection bubbles could be a key element for conflict prediction, especially during the strategic phase, where they ensure that the drone remains separated from other aircraft as long as it stays within its bubble. In the tactical phase, they can also facilitate conflict prediction by quickly computing updated bubble intersections.
<b>Operation plan preparation</b>	The calculation and display of protection bubble sizes based on the associated local air risk (including undeclared traffic) can significantly help the drone operator in developing an effective and secure flight path.
<b>Geo-awareness</b>	This service aims to provide drone operators with information regarding predefined UAS geographical zones. We propose to enhance this information by presenting associated risk layers based on the reasons for creating these zones. Providing density layers by traffic type is also a pertinent approach to provide maximal information to drone operators. In the tactical phase, generating 4D bubbles whose sizes vary depending on potential air risk can benefit this service, particularly in the context of the dynamic geofencing concept. By integrating both separation from planned traffic and the risk of encountering undeclared potential traffic, these bubbles can be a natural implementation of dynamic geofences.
<b>Monitoring and emergency management</b>	As a complement to the geo-awareness service, 4D protection bubbles can be utilized to detect potential breaches of airspace limitations. This feature allows for early detection and mitigation of potential air incidents, providing an added layer of safety for drone operations.
<b>Risk analysis assistance</b>	The collection of risk layers and their utilization in the formation of 4D protection bubbles can serve as a fundamental set of tools for this service. One of the main goals of this service could be to manage abnormal situations that are considered in the operational use case ( <i>note</i> : this aspect is not covered in this paper).

## VI. Conclusions, limits and perspectives

In order to manage a complex traffic of drones in an urban environment, we developed a concept of operations based on 4D protection bubbles to manage potential conflicts between drones. From initial 4D trajectories submitted in flight authorization requests, conflict-free bubbles are calculated to keep each drone separated from any other planned traffic. The size of these protection bubbles can be dynamically adjusted based on the presence of other planned operations in the vicinity of the drone.

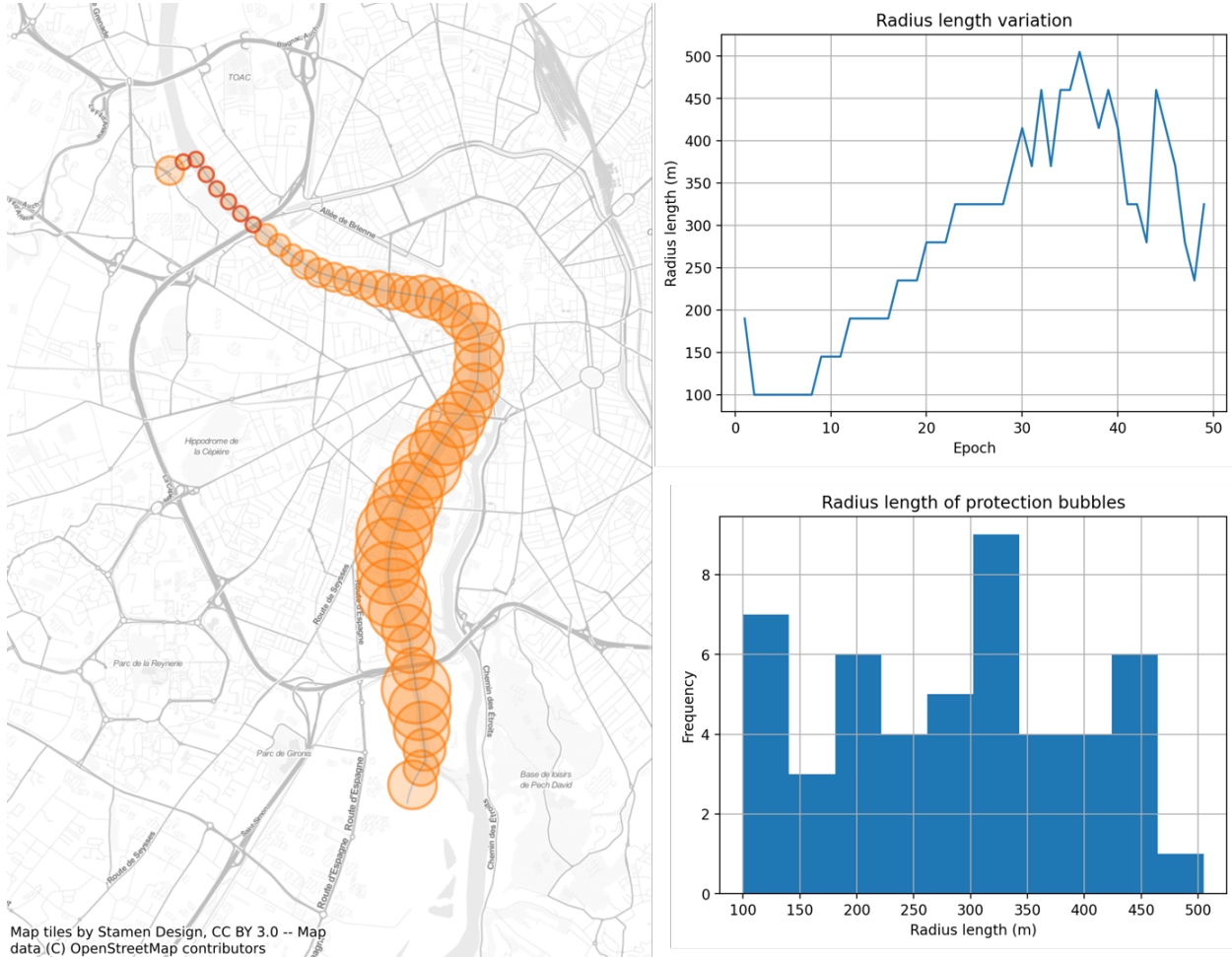
We present an extension of the 4D protection bubble concept to address air risk, specifically the possibility of collision with other aircraft not considered in the initial 4D optimization. To evaluate and mitigate this risk, we utilize data from relevant UAS geographical zones and historical low-altitude traffic data to assess the probability of encountering different types of traffic. We introduce a basic model that compiles this data in the form of risk layers, which are used to calculate the size of the protection bubbles along the trajectory. The bubble size is determined by balancing the risk scores provided by the different layers, as illustrated by the example presented in Appendix.

In the near future, we aim to reconsider the operation concept by studying how certain "unplanned traffic" can be partially integrated into optimization through agreement protocols. Additionally, updating 4D trajectories could be facilitated by the introduction of personal parking zones, defined as an element of the drone's 4D trajectory.

The developed 4D framework has the potential to facilitate the integration of numerous level 2 U-space services. In particular, this framework provides a means to improve the functionality of the geo-awareness service and serves as a foundational component for the upcoming risk analysis assistance service.

The air risk model presented here is limited and would benefit from a set of improvements, both in terms of proximity risk and traffic density layers. Moreover, combining the air risk with ground risk [19] is necessary. Therefore, our future model should integrate several additional layers, including population density as described in [20]. Our next objective will be to determine whether this model can provide quantitative risk assessment as a supplement to the qualitative risk assessment defined in the Specific Operation Risk Assessment (SORA) methodology [21].

## Appendix



**Fig. 8 Example of 4D protection bubbles after a risk layers trade-off**

## Acknowledgments

This research has received partial funding from the French Directorate General for Civil Aviation (DGAC). The funding is part of the French research project PHYDIAS, which aims to enhance the safety of drones and is coordinated by the DGAC. The authors extend their gratitude to their colleagues Christel Seguin, Alexandre Amiez, Sergio Pizziol and Judicaël Bedouet for their operational expertise and valuable feedback during the development of this paper.

## References

- [1] Kopardekar, P., Rios, J., Prevot, T., Johnson, M., Jung, J., and Robinson, J. E., "Unmanned aircraft system traffic management (UTM) concept of operations," *AIAA Aviation and Aeronautics Forum (Aviation 2016)*, 2016.
- [2] Federal Aviation Administration, "Unmanned Aircraft System (UAS) Traffic Management (UTM) Concept of Operations v2.0," Technical report, Federal Aviation Administration, 2020. URL [https://www.faa.gov/sites/faa.gov/files/2022-08/UTM\\_ConOps\\_v2.pdf](https://www.faa.gov/sites/faa.gov/files/2022-08/UTM_ConOps_v2.pdf).

- [3] SESAR Joint Undertaking, “U-space: Blueprint,” Technical Report 2019-04, SESAR Joint Undertaking, 2019. URL <https://www.sesarju.eu/sites/default/files/documents/reports/U-space%20Blueprint%20brochure%20final.PDF>.
- [4] Barrado, C., Boyero, M., Brucculeri, L., Ferrara, G., Hately, A., Hullah, P., Martin-Marrero, D., Pastor, E., Rushton, A. P., and Volkert, A., “U-space concept of operations: A key enabler for opening airspace to emerging low-altitude operations,” *Aerospace*, Vol. 7, No. 3, 2020, p. 24.
- [5] CORUS-XUAM, “U-space ConOps (edition 3.10),” Technical Report D4.1, CORUS-XUAM, 2022. URL [https://corus-xuam.eu/wp-content/uploads/2022/11/CORUS-XUAM-D4.1-delivered\\_3.10.pdf](https://corus-xuam.eu/wp-content/uploads/2022/11/CORUS-XUAM-D4.1-delivered_3.10.pdf).
- [6] International Civil Aviation Organization, “Unmanned Aircraft Systems Traffic Management (UTM) – A Common Framework with Core Principles for Global Harmonization Edition 3,” Technical report, ICAO, 2023. URL <https://www.icao.int/safety/UA/Documents/UTM%20Framework%20Edition%203.pdf>.
- [7] European Union, “Commission implementing regulation (EU) 2019/947 of 24 May 2019 on the rules and procedures for the operation of unmanned aircraft,” Official Journal of the European Union, 2019. URL <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R0947>.
- [8] European Union, “Commission implementing regulation (EU) 2021/664 of 22 April 2021 on a regulatory framework for the U-space,” Official Journal of the European Union, 2021. URL <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021R0664>.
- [9] Dubot, T., and Joulia, A., “Towards U-space conflict management services based on 4D protection bubbles,” *AIAA AVIATION 2021 FORUM*, 2021, p. 2347.
- [10] Joulia, A., and Dubot, T., “Analysis and assessment of U-space tactical conflict management services,” *AIAA AVIATION 2022 Forum*, 2022, p. 3543.
- [11] Undertaking, S. J., “Smart ATM - U-space,” <https://www.sesarju.eu/U-space>, 2023.
- [12] SESAR Joint Undertaking, “U-space - Supporting safe and secure drone operations in Europe,” Technical Report, SESAR Joint Undertaking, 2020. URL <https://www.sesarju.eu/sites/default/files/documents/reports/U-space%20research%20innovation%20results.pdf>.
- [13] Le Tallec, C., and Joulia, A., “IFATS: 4D contracts in 4D airspace,” *AIAA Infotech@ Aerospace 2007 Conference and Exhibit*, 2007, p. 2778.
- [14] Joulia, A., Riviere, T., and Le Tallec, C., “Impact of aircraft guidance and navigation on 4D contracts generation and execution-example of the 4DCo-GC project,” *AIAA Guidance, Navigation, and Control (GNC) Conference*, 2013, p. 4890.
- [15] Hoekstra, J. M., Ellerbroek, J., Sunil, E., and Maas, J., “Geovectoring: reducing traffic complexity to increase the capacity of uav airspace,” *International Conference for Research in Air Transportation, Barcelona, Spain*, 2018.
- [16] Joulia, A., Dubot, T., and Bedouet, J., “Towards a 4D traffic management of small UAS operating at very low level,” ICAS, 30th Congress of the International Council of the Aeronautical Sciences, 2016.
- [17] Aeronautical Information Service, “User Guide for UAS Geographical Zone Dataset,” Technical Report, General Directorate of Civil Aviation (DGAC), 2022. URL [https://www.sia.aviation-civile.gouv.fr/pub/media/news/file//g/u/guide\\_utilisation\\_ds\\_uas\\_1.pdf](https://www.sia.aviation-civile.gouv.fr/pub/media/news/file//g/u/guide_utilisation_ds_uas_1.pdf).
- [18] Schäfer, M., Strohmeier, M., Lenders, V., Martinovic, I., and Wilhelm, M., “Bringing up OpenSky: A large-scale ADS-B sensor network for research,” *IPSN-14 Proceedings of the 13th International Symposium on Information Processing in Sensor Networks*, IEEE, 2014, pp. 83–94.
- [19] Bertrand, S., Raballand, N., Viguiet, F., and Muller, F., “Ground risk assessment for long-range inspection missions of railways by UAVs,” *2017 International Conference on Unmanned Aircraft Systems (ICUAS)*, IEEE, 2017, pp. 1343–1351.
- [20] Milano, M., Primatesta, S., and Guglieri, G., “Air Risk Maps for Unmanned Aircraft in Urban Environments,” *2022 International Conference on Unmanned Aircraft Systems (ICUAS)*, IEEE, 2022, pp. 1073–1082.
- [21] Olive, X., and Le Blaye, P., “A Quantitative Approach to Air Traffic Safety at Very Low Levels,” *Engineering Proceedings*, Vol. 28, No. 1, 2022, p. 1.